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ABSTRACT

This paper relates philosophical and psychological concerns in formulating a theory of teaching and learning. The laboratory exercise is shown to be a paradigm case of the theory, and a means by which students can be taught to think. The laboratory exercise is presented as a means to demonstrate a facet of the conceptual nature of science and to teach students that the construction of an experimental design represents a kind of analogy based upon the idea that what happens in the laboratory is an analogue of what occurs in nature. Anecdotal evidence from classroom experience with this teaching strategy is discussed. (Author/CS)

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ANALOGUE MODELS IN THE LABORATORY EXERCISE: ONE METHOD FOR TEACHING TO THINK

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Introduction:

It is generally agreed that the construction and use of models form an integral part in the development of knowledge in the sciences (Hempel, 1965; Campbell, 1953; Turbayne, 1970, Harre, 1972). While there is some disagreement among these philosophers about the number and kinds of models, and the extent of their involvement in the construction of scientific knowledge, there is agreement about their function. Constructed models attempt to cast a familiar system of known structure and laws onto an unfamiliar domain where a structure and covering laws are sought. It appears that a model, which functions to offer a conceptual framework of description and explanation of some natural phenomena, is necessary for the formation of a theoretical system. However, in this paper I wish to explore a different, but related, aspect of models, and how their construction, use, and analysis has important implications in science education.

My thesis is this: the construction of a laboratory exercise is equivalent to the construction of a purposefully contrived analogue model which offers an associated description of some natural phenomena

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that is addressed in the experiment. Further, the construction, use, and analysis of these analogue models in the classroom laboratory exercise teach students to think. I will examine, first, the definition of thinking offered by Belth (1977). Next, I will discuss the four types of models described by Black (1962), while concentrating on his analysis of analogue models. Aspects of Black's analysis will be examined to see how they bear on the use of analogue models in the laboratory. Also included in that part of the paper will be an examination of other contributions to understanding analogue models from Hesse (1966) and Belth (1977). In addition, the psychological dimension involved in the construction and use of analogue models will be mentioned using the cognitive learning theory of Ausubel (1978) and Novak (1977).

Definition of Thinking:

Belth in his PROCESS OF THINKING (1977) has characterized the act of thinking as the,

> follow[ing] out all that is entailed in some model, analogy or metaphor deliberately constructed so that we entertain, in some systematic way, events of our experience (p. xvii).

From this definition, two distinctive aspects of the thinking act become evident, and both must be present in order for the activity to be complete. First, thinking involves the "employment of models" (p. xvii). As a house builder keeps a mental picture in his mind, or works from a set of blueprints, to construct a home, a model is in use; a chef who refers to a recipe, which is a kind of model, constantly keeps the relative proportions of the ingredients in mind as a gourmet

delight is created; a psychiatrist can work from a psychoanalytic model; the physicist will use an electromagnetic model or a quantum model to explain the nature of light.

But anyone can use one model or another and not realize it. Thus, thinking must have a second aspect. In addition to using a model, thinking must involve a "reflection upon itself" (p. xvii) which addresses the model directly, assessing and analyzing its adequacy.

Thinking, then, is a two-fold activity which is directed both toward the event we wish to study by employing some model to make sense of that event, and away from the event to confront intellectually the model to examine its underlying premises and to find deeper meaning contained within.

Types of Models:

Black in his MODELS AND METAPHORS (1962) has identified four types of models: the scale, the mathematical, the analogue, and the theoretical. A scale model is produced as the elements of some system are proportionally changed within the context of a new medium (pp. 220-221). The function of the scale model is to reproduce as faithfully as possible the size, shape, or spacial relations among the parts of the original. Toy cars, maps, time lines in history classes, and larger than life models of insects are all examples of scale models.

The mathematical model attempts to take an original field and project it ". . . upon the abstract domain of sets, functions, and the like that is the subject matter of the correlated mathematical theory" (p. 223). Mathematical models are more abstract than the original since

they restrict the variables of the event that is to be studied. This is done so that quantification of certain aspects of the event can be done.

The third type of model identified by Black is the analogue model. Unlike the scale model where a point by point characterization of the original is important, analogue models seek to demonstrate or illustrate the web of relationships in the original. Thus, analogues are necessarily more abstract than scale models, since they are concerned with the relations among the parts rather than with the parts directly (p. 223). Common analogue models include mechanical systems imposed on psychological events, the solar system as an analogue for the atom, or corporate structures compared to well-oiled machines. These are just brief remarks to establish a point of comparison for the theoretical model that will follow. The nature of analogue models will be discussed in greater length further in this paper.

The fourth and final type of model that Black identifies is the theoretical model. At first glance, a theoretical model closely resembles the analogue model, and essentially, the construction of both are similar. However, their distinction becomes evident as we examine the function of the theoretical model. A model becomes theoretical as the language implicit in the model is cast upon and integrated through the description and explanation of the original domain that is in need of some structure. Thus, as Black states, a theoretical model "work[s] not by analogy, but through and by means of an underlying analogy" (p. 229, author's emphasis).

Let me now return to a more complete description of the structure and nature of the analogue model. This will provide the foundation of showing how the laboratory experiment is a constructed analogue that has the purpose of representing, among other things, the web of relationships among the parts that comprise that experiment.

Black defines the analogue model as "some material object, system, or process designed to reproduce as faithfully as possible in some new medium the structure or web of relationships in the original" (1962, p. 222, author's emphasis). This statement needs some expansion to examine its meaning in greater detail.

Since scale models are primarily tangible representations of some other tangible, physical object, they are restricted in the number and kinds of representations that can be created. Analogue models are more flexible. Because the purpose of the analogue is to represent the relationships among the parts of the original, any source which illustrates those relationships becomes a candidate as an analogue model.

What degree of structure of relationships is evident in the construction of analogue models? This characteristic is illustrated by the model's dominating principle of isomorphism (Black, p. 222). As the degree of isomorphism increases between the model and the original, the applicability of the model becomes more powerful, more persuasive. The epitome of isomorphism is, of course, duplication of the original, where the analogue dissolves. Since no analogue can entirely represent the original without itself becoming a duplication of the original, there are some properties that the original and the analogue do not

share. Hesse in her MODELS AND ANALOGIES IN SCIENCE (1966) has defined these as the model's negative properties. Those qualities that the model and the original do share, and which represent its degree of isomorphism are called its positive properties. And those qualities of the model that represent neither positive or negative properties are called its neutral properties.

But it must be remembered that no model, no matter how persuasive, provides proof of its own adequacy. Any model must be validated independently by other criteria other than its intrinsic isomorphism. As Black states, "[a]nalogue models furnish plausible hypotheses, not proofs" (1962, p. 223).

Another important condition in Black's definition of analogue models deals with his use of the word "new." While there can be analogues that are of course new, that does not mean that the transfer of medium must be novel. All that is implied is that the medium be different than the original. Different in the sense that there is a transfer from one medium to another, even if that transfer has occurred a number of times before. Now, this may seem like a trivial point, but it brings up a dilemma that should be noted. When this transfer occurs so many times, the problem arises of what happens when the difference, the transferal, becomes commonplace? It seems that when this happens the analogical basis disappears (at least consciously), and will not be evident upon cursory examination of the model. A case in point is Hooke's analogy of honeycomb "cells" to the little chambers he saw in the magnified cork. The term "cell" since then has been used for so long, and has undergone such a metamorphosis of meaning, that its

initial analogical quality has become obscured.

Another condition of the nature of analogues deals with the test for the "fit" of that model. First, we must be concerned with the degree of isomorphism between the elements of the original and the elements of the model. How abstract is the connection between them? Second, we must be concerned with empirically validating the "fit". Are some models more easily subject to empirical validation than others? Belth (1977) has developed a classification system that places any constructed models along a spectrum that has the purpose of illustrating this degree of abstraction and ability to be empirically validated. At one end are the "hard" models, which possess a close resemblance between the elements of the original and the model, and which can easily be subject to empirical validation. At the other end of the spectrum are the "soft" models, which possess a highly abstract isomorphism and an intrinsic inability to be empirically validated.

Three examples should clarify these distinctions. The Watson and Crick model of DNA is a very hard model. First, it was inferred from the research that the DNA molecule must look like a ladder. A ladder composed of two ribose-sugar-phosphate chains, one at either end. The "rungs" of the ladder were pairs of nitrogenous bases, held together by a weak hydrogen bond. Since there existed a strong physical resemblance between the DNA molecule and the model employed to describe it, and since this model lent itself to empirical validation, the ladder analogue for DNA is considered a very hard model.

As we move from that end of the spectrum, we find softer models. For example, a model of psychology in which we assign steps to cognitive

development, as Piaget does, is based on a staircase analogue. Since no one would seriously entertain a direct resemblance of a staircase within the human mind, this is an example of a softer model. However, the Piagetian analogue is subject to empirical validation, as the hundreds of studies done with this model will attest. Because of that characteristic, the Piagetian staircase analogue falls somewhere between the hardest and the softest of models.

Toward the softest of models we might examine Dante's INFERNO. Here we have an analogue which is based upon a different kind of staircase, descending down farther and farther into Hell. Now, this is a very abstract notion of Hell, for the idea that some physical object like a staircase is present in a world inhabited by spirits is intellectually taxing to say the least. Further, since there can be no empirical test of that model, it represents the softest of analogues.

Now, I have chosen these three examples quite purposely to illustrate the point that the same basic analogy -- a staircase with steps or a ladder with rungs -- can have very different degrees of hardness or softness, depending on the discipline in which the analogue is created. In the natural sciences, the intention is to create the hardest models possible so that a high degree of empirical validation can be initiated. Other disciplines, like psychology, must deal with more abstract realms, since the original domain is composed of such non-tangibles as "mind" or "drives." And in theology, we attempt to fashion models of very abstract ideas with no capacity to perform an empirical test of the model.

There is a psychological dimension to the successful use of analogues which also must be mentioned because of its direct effect on the understanding of the analogue model, and thus, to learning. When one system is cast as an analogue upon another system, it must be remembered that the model demonstrates a web of relationships that is found to be particularly inviting and useful. Now, this system-turned-model is conceptual in nature. That is, the structure of the analogue is composed of the interrelations among the concepts that ultimately become the model. Understanding the conceptual relationships within that system becomes a prerequisite for the successful use of the analogue.

Ausubel's (1978) and Novak's (1977) assimilation theory of learning accounts for this need of understanding the conceptual nature of the analogue model quite nicely. The theory states that concepts which are learned meaningfully are linked in a substantive way to other concepts which already exist in the cognitive structure of the individual. The antithesis of this claim is that those concepts which are learned in a rote fashion are not linked or connected in any substantive way to existing concepts. As new concepts are learned meaningfully, a change in the cognitive structure occurs. New relationships are established, new hierarchies are developed, meanings of existing concepts are modified to accomodate the new information.

All this has important ramifications for understanding the use of analogue models. To comprehend, for instance, an evolutionary model of society requires, first, that the conceptual structure of the evolutionary system be meaningfully learned. That is, we cannot expect to find the web of relationships between "variations" and "environmental

changes" in a society if first these concepts have not been meaningfully learned by the individual.

Let me now focus in upon the use of analogue models in the laboratory, considering the features that I have outlined in the preceding parts of this paper.

Analogue Models in the Laboratory:

All this has a bearing on the experimental method of science when we realize that models abound in the laboratory. Experiments are conducted to test the adequacy of some theoretical model, a mathematical model can be employed when it is decided what elements will be quantified and what appropriate mathematical theory will be used to treat the data. But at the heart of the experimental method is the construction of an analogue model. An analogue model which attempts to fashion a very hard model of our perceptions of a natural phenomenon. Realizing this, and also that the experimental method is one of our surest forms of empirical validation, the only analogic quality we must satisfy is the degree of resemblance of the isomorphism.

Referring again to Hesse's trichotomy of analogic properties, the adequacy of any experiment lies within its ability to reflect as many positive properties as possible. That is, a wide range of positive correspondence should exist between the original (nature) and the analogue (the experiment). This is done to reduce the number of negative properties to such a point that we will be able to state, with some degree of certainty, that the experimental analogue approaches the original, and that our subsequent conclusions about nature in general

are given greater validity. Further, as we progress through a series of experiments, we might find conditions that were thought to have no effect on the results. These would be the neutral properties.

Let me examine an illustration of an experimental procedure that reflects the three properties. Several years ago, there were reports of a series of Canadian studies linking cancer in test rats with the administration of the artificial sweetener saccharin. High doses of the sweetener were given to the animals over a period of time, and a significant number of these rats were found to have malignant tumors, caused, as inferred from the observations, from the presence of saccharin. The implication was, of course, that if humans consume this product, they too will develop cancer. But there has been quite a clamor about that research which surrounds the design of the experiments, or as I have argued here, the positive and negative properties of the experimental analogue. Is the test animal an adequate representation of the human? It is a mammal, and as such, the rat should have many of the same physiological qualities as humans (positive property). But they are not human, so there must be some physiological qualities that they do not share with humans (negative property). The presence of saccharin (positive property) may have some effect on humans, but do the levels of doses administered to the rats realistically reflect the amount that would be consumed by a human (negative property)? What other conditions about the rats might affect the results? Were they a sample of a particular strain of rats which are cancer prone? If so, would that be considered a negative or perhaps even a neutral property?

The Laboratory Exercise as an Analogue Model:

All this leads to a consideration of the laboratory activity as used in our classrooms. Since we are teachers, and not scientists, the objective of using the experimental method changes. In our classrooms, we are not involved with the sorting out of natural phenomena: that is the job of the scientist. Rather, our objective is to foster thinking skills in the learner by providing the means by which analogies are constructed, used, and analyzed within the natural sciences.

The first example is from a unit on human physiology taught to seventh grade students in a rural central school in upstate New York during the academic year 1977-1978. The classes were of average ability, and heterogeneously grouped. Initially, the students were given an assignment to read a section of a text on the human digestive system, and to prepare notes which summarized the anatomical and physiological aspects of digestion. In preparation for the laboratory exercise, a class discussion covered most of the major concepts involved with this topic.

When the students were conceptually prepared for the laboratory exercise, I posed the task: prepare a laboratory procedure that will represent as closely as possible how digestion occurs in the human digestive system. The six lab groups were given the opportunity to decide what part of the digestive system they wanted to represent. Two groups chose the mouth, two chose the stomach, and two chose the small intestine. The students were to write a procedure that was conceptually consistent with what they already understood about the

anatomy of the alimentary canal and the process of digestion therein. During this initial stage of the lesson, I went from group to group suggesting reference sources for assistance and providing information on available laboratory equipment that was needed. Using these reference sources and equipment from the laboratory, the students designed and executed their laboratory experiments. Observations were made, and conclusions reached.

On the day following the execution of the procedures, the students were asked to sit in a circle and to take part in a seminar-like discussion of their results. The function of the seminar was to analyze the constructed analogue models to test their "fit" or degree of isomorphism. Each group was responsible for reporting the procedure, observations, and conclusions of their research. As each group reported their results, other groups were encouraged to question each facet of the research. The procedures were analyzed relative to whether they adequately reflected that part of the human digestive system, and the conditions under which the digestion took place. The observations were analyzed relative to their ability to reflect the adequacy of the constructed model. And the conclusions were examined for consistency.

Questions were asked by me and other students to nudge the class into analyzing their constructed models. Below are some representative questions. Because I did not use the specific terms "analogue," "positive property," "negative property," etc., I have next to each of these questions an implied question which shows what aspect

of the model I wanted to students to examine.

QUESTIONS POSED TO THE STUDENTS	IMPLIED QUESTION
"Why did you use the enzyme pepsin for the stomach experiment?"	"Is the use of pepsin a positive property?"
"Will the fact that you used a test tube rather than a mouth affect your results?"	"Is the test tube a negative or neutral property?"
"You left the experiment out on the lab counter overnight. What is different about that and what happens in your stomach?"	"Are light, temperature, exposure to air, non-churning of the 'stomach," and time present in the 'stomach' positive, negative, or neutral properties?"
"Is the concentration of ptyalin in your experiment the same as the concentration in your mouth?"	"Is concentration of enzyme a positive, negative, or neutral property?"

These are just some of the representative questions that can be asked of the class during the seminar. The actual questions asked will depend on the degree of isomorphism and level of abstraction that the students will have built into their constructed analogue. In some cases, the analyses that result from the seminar could lead to another, "harder" round of experiments.

The second example is taken from a unit on weathering and erosion taught to eighth grade students in the same rural school. In this example, the presentation was changed slightly. Instead of having the students begin by constructing the analogue, I developed the exercise and had the students conduct the procedure, collect the necessary observations, and reach the conclusions.

The experiment itself dealt with the affect that extreme temperature changes have on the weathering of rocks. The procedure asked the

students to heat a piece of rock over a bunsen burner for a period of three minutes. Then they were to pick up the rock with tongs, and plunge the rock into an aluminum beaker of cold water. Observations were made about the condition of the rock after it had been heated and cooled rapidly.

The procedure was obviously an example of an analogue carried to extremes. That one rock was to represent all types of rock, the extreme heat of the bunsen burner was to represent the Sun's heat, the rapid cooling in water, the change of temperature from day to night. All these pushed the analogue to its intellectual limits. In the seminar discussion which followed the laboratory exercise, the students were asked to evaluate the experimental procedure to see if it adequately represented what occurs in nature. Based on the reading that the students had done on the topic, they began to analyze the procedure to test its adequacy. Questions were posed to the students, as in the previous example. Again, another level of implied questions are provided to more clearly identify the aspect of the analogue model I wished the students to examine.

QUESTIONS POSED TO THE STUDENTS	IMPLIED QUESTIONS
"What were the parts of the procedure that represented what could be found in nature?"	"What were the positive properties of this experimental analogue?"
"What were the parts of the procedure that represented what is not found in nature?"	"What are the negative properties of this experimental analogue?"
"How could the procedure be changed to more closely represent the kind of weathering accomplished by temperature change in nature?"	"What would you do to the negative and neutral properties to make them positive properties?"

As before, this procedure could have led to another procedure that more adequately represented what was occurring during the weathering process. That would have increased the degree of isomorphism and resemblance in the procedure.

Summary:

The objective of using the laboratory exercise in the classroom can change if we realize that the experimental method of science involves the construction, use, and analysis of analogue models. Models which attempt to fashion a high degree of physical isomorphism between what happens in nature and what is constructed in the laboratory. Rather than having the objective of teaching students some aspect of subject matter, the student is taught to think, defined as the employment and reflection upon some model in operation. As the teacher considers the elements of the analogue model, isomorphism, change of medium, range of positive, negative, and neutral properties, and relative hardness and softness, the concept of teaching for this method will emerge.

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